Basic_sCO2_States

October 10, 2021

[1]:
```
# Dictate the environment's loctaion of REFPROP
import os
os.environ['RPPREFIX'] = r'C:/Program Files (x86)/REFPROP'
```

[2]:
```
# Import the main class from the Python library
from ctREFPROP.ctREFPROP import REFPROPFunctionLibrary

# Imports from conda-installable packages
import pandas as pd

# Import numpy
import numpy as np

# Import matplotlib for plotting
import matplotlib.pyplot as plt

# Import Math for common values such as PI
import math
```

[3]:
```
# Instantiate the library, and use the environment variable to explicitly state␣
↪which path we want to use.
# As mentioned above, this will be changed to call the correct REFPROP␣
↪functions to be used
# with MINI-REFPROP and 32-bit python.
# If using MINI-REFPROP and 32-bit python please make the following changes
# RP = REFPROPFunctionLibrary('C:/Program FIles (x86)/MINI-REFPROP\\REFPROP.
↪DLL')
RP = REFPROPFunctionLibrary(os.environ['RPPREFIX'])
```

[4]:
```
# This will call which root directory that will be used for the program.
RP.SETPATHdll(os.environ['RPPREFIX'])
```

[5]:
```
# Get the unit system we want to use (Mass base SI gives units in
# K, Pa, kg, m, N, J, W, and s)
MASS_BASE_SI = RP.GETENUMdll(0, "MASS BASE SI").iEnum
```

0.0.1 Basic sCO2 States Derived

[6]:
```
m_dot = .2 # kg/s of mass flow rate of sCO2
```

Outlet of Heat Source, Inlet of Engine

[7]:
```
T2 = 88 # [C]
P2 = 2500 # [psia]

T2 = T2 + 273.15 # Convert C to Kelvin
P2 = P2 * 6894.8 # convert psia to Pa

print("Pressure at Outlet of Heat Source =", P2/6894.8, "psia")
print("Temperature at Outlet of Heat Source =" , (T2 - 273.15) * (9/5) + 32,␣
 ↪"F")
```

```
Pressure at Outlet of Heat Source = 2500.0 psia
Temperature at Outlet of Heat Source = 190.4 F
```

[8]:
```
# Obtain fluid properties from the pressure and enthalpy outlined above
State_2 = RP.REFPROPdll("CO2","PT","H;D;V;S;CP/CV;W;TCX;VIS;PRANDTL",␣
 ↪MASS_BASE_SI,0,0,P2,T2,[1.0])

# Outputs will be placed into data frame for organization
State_2 = pd.DataFrame(State_2.Output[0:9],
            index = ['Enthalpy [J/kg]','Density [kg/m^3]', 'Volume [m^3/kg]',␣
 ↪'Entropy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
 ↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 2'])

# Display the data frame
State_2
```

[8]:

	State 2
Enthalpy [J/kg]	414772.202437
Density [kg/m^3]	462.360653
Volume [m^3/kg]	0.002163
Entropy [J/kg]	1619.615557
CP/CV	2.880774
Speed of Sound	291.838963
Thermal Cond. [W/(mK)]	0.053589
Viscosity [Pa-s]	0.000035
Prandtl	1.714147

Outlet of Engine, Inlet of Heat Exchanger

[9]:
```
# Engine Parameters
mass_cylinder = State_2.loc['Density [kg/m^3]', 'State 2'] * .000308276
```

```
State_3_den = mass_cylinder / .000454574

# With Isentropic expansion
State_3_entr = State_2.loc['Entropy [J/kg]', 'State 2']

State_3_isen = RP.REFPROPdll("CO2","DS","P;T;V;H;CP/CV;W;TCX;VIS;PRANDTL",␣
↪MASS_BASE_SI,0,0,State_3_den,State_3_entr,[1.0])

# Outputs will be placed into data frame for organization
State_3_isen = pd.DataFrame(State_3_isen.Output[0:9],
            index = ['Pressure [Pa]', 'Temperature [K]', 'Volume [m^3/kg]',␣
↪'Enthalpy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 3 Isentropic'])
```

[10]:
```
# Account for Issentropic Efficiency
Isen_eff = .7
State_3_enth_new = State_2.loc['Enthalpy [J/kg]','State 2'] - (Isen_eff *␣
↪(State_2.loc['Enthalpy [J/kg]','State 2'] - State_3_isen.loc['Enthalpy [J/
↪kg]', 'State 3 Isentropic']))

# Using Pressure and enthalpy find the states of the fluid at the Outlet of␣
↪Engine

State_3 = RP.REFPROPdll("CO2","PH","D;T;V;S;CP/CV;W;TCX;VIS;PRANDTL",␣
↪MASS_BASE_SI,0,0,State_3_isen.loc['Pressure [Pa]', 'State 3␣
↪Isentropic'],State_3_enth_new,[1.0])

# Outputs will be placed into data frame for organization
State_3 = pd.DataFrame(State_3.Output[0:9],
            index = ['Density [kg/m^3]','Temperature [K]', 'Volume [m^3/kg]',␣
↪'Entropy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 3'])
```

Outlet of Heat Exchanger, Inlet to Compressor

[11]:
```
P4 = State_3_isen.loc['Pressure [Pa]', 'State 3 Isentropic']

Q_out = -8.2 # kW heat removed by Heat Exchanger

h4 = Q_out * 1000 / (m_dot) + State_3_enth_new
```

[12]:
```
# Obtain fluid properties from the pressure and enthalpy outlined above
```

```
State_4 = RP.REFPROPdll("CO2","PH","T;D;V;S;CP/CV;W;TCX;VIS;PRANDTL",␣
↪MASS_BASE_SI,0,0,P4,h4,[1.0])

# Outputs will be placed into data frame for organization
State_4 = pd.DataFrame(State_4.Output[0:9],
            index = ['Temperature [K]','Density [kg/m^3]', 'Volume [m^3/kg]',␣
↪'Entropy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 4'])
```

Outlet of Compressor, Inlet to Heat Source Isentropic

[13]:
```
# Find the Isentropic Outlet of the Compressor
State_1_isen = RP.REFPROPdll("CO2","PS","T;D;V;H;CP/CV;W;TCX;VIS;PRANDTL",␣
↪MASS_BASE_SI,0,0,P2,State_4.loc['Entropy [J/kg]', 'State 4'],[1.0])
State_1_isen = pd.DataFrame(State_1_isen.Output[0:9],
            index = ['Temperature [K]','Density [kg/m^3]', 'Volume [m^3/kg]',␣
↪'Enthalpy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 1 Isentropic'])
```

[14]:
```
# Account for Issentropic Efficiency
Isen_eff = .85
State_1_enth_new = h4 + ((State_1_isen.loc['Enthalpy [J/kg]', 'State 1␣
↪Isentropic'] - h4)/Isen_eff)
```

[15]:
```
State_1 = RP.REFPROPdll("CO2","PH","T;D;V;S;CP/CV;W;TCX;VIS;PRANDTL",␣
↪MASS_BASE_SI,0,0,P2,State_1_enth_new,[1.0])

# Outputs will be placed into data frame for organization
State_1 = pd.DataFrame(State_1.Output[0:9],
            index = ['Temperature [K]', 'Density [kg/m^3]', 'Volume [m^3/kg]',␣
↪'Entropy [J/kg]',
                     'CP/CV', 'Speed of Sound', 'Thermal Cond. [W/(mK)]',␣
↪'Viscosity [Pa-s]', 'Prandtl'],
            columns = ['State 1'])
```

[16]:
```
State_2.loc['Pressure [Pa]', 'State 2'] = P2
State_2.loc['Temperature [K]', 'State 2'] = T2
State_3_isen.loc['Density [kg/m^3]', 'State 3 Isentropic'] = State_3_den
State_3_isen.loc['Entropy [J/kg]', 'State 3 Isentropic'] = State_3_entr
State_3.loc['Enthalpy [J/kg]', 'State 3'] = State_3_enth_new
State_3.loc['Pressure [Pa]', 'State 3'] = State_3_isen.loc['Pressure [Pa]',␣
↪'State 3 Isentropic']
State_4.loc['Pressure [Pa]', 'State 4'] = P4
```

```python
State_4.loc['Enthalpy [J/kg]', 'State 4'] = h4
State_1_isen.loc['Entropy [J/kg]', 'State 1 Isentropic'] = State_4.loc['Entropy␣
↪[J/kg]', 'State 4']
State_1_isen.loc['Pressure [Pa]', 'State 1 Isentropic'] = P2
State_1.loc['Enthalpy [J/kg]', 'State 1'] = State_1_enth_new
State_1.loc['Pressure [Pa]', 'State 1'] = State_1_isen.loc['Pressure [Pa]',␣
↪'State 1 Isentropic']
```

[17]:
```python
# Combine the data frames into one data frame for ease of use
sCO2_States = pd.concat([State_1_isen, State_1, State_2, State_3_isen, State_3,␣
↪State_4], axis =1)

# Reorder the Data Frame
sCO2_States = sCO2_States.reindex(["Pressure [Pa]", "Temperature [K]", 'Density␣
↪[kg/m^3]', 'Volume [m^3/kg]', 'Enthalpy [J/kg]',
                     'Entropy [J/kg]', 'CP/CV', 'Speed of Sound', 'Thermal Cond.
↪ [W/(mK)]', 'Viscosity [Pa-s]',
                     'Prandtl' ])

# Display the data frame
sCO2_States
```

[17]:
```
                       State 1 Isentropic       State 1       State 2  \
Pressure [Pa]                1.723700e+07  1.723700e+07  1.723700e+07
Temperature [K]              3.474071e+02  3.484821e+02  3.611500e+02
Density [kg/m^3]             5.566761e+02  5.484311e+02  4.623607e+02
Volume [m^3/kg]              1.796377e-03  1.823383e-03  2.162814e-03
Enthalpy [J/kg]              3.759455e+05  3.791278e+05  4.147722e+05
Entropy [J/kg]               1.509966e+03  1.519112e+03  1.619616e+03
CP/CV                        3.177562e+00  3.167072e+00  2.880774e+00
Speed of Sound               3.109282e+02  3.085568e+02  2.918390e+02
Thermal Cond. [W/(mK)]       6.172936e-02  6.100759e-02  5.358901e-02
Viscosity [Pa-s]             4.187644e-05  4.117298e-05  3.479425e-05
Prandtl                      2.012615e+00  1.992961e+00  1.714147e+00

                       State 3 Isentropic       State 3       State 4
Pressure [Pa]                8.351911e+06  8.351911e+06  8.351911e+06
Temperature [K]              3.138944e+02  3.150604e+02  3.105478e+02
Density [kg/m^3]             3.135566e+02  2.976036e+02  4.127311e+02
Volume [m^3/kg]              3.189217e-03  3.360175e-03  2.422885e-03
Enthalpy [J/kg]              3.921162e+05  3.989130e+05  3.579130e+05
Entropy [J/kg]               1.619616e+03  1.641230e+03  1.509966e+03
CP/CV                        5.988800e+00  5.135798e+00  1.445877e+01
Speed of Sound               2.030412e+02  2.063522e+02  1.896631e+02
Thermal Cond. [W/(mK)]       4.986973e-02  4.634190e-02  7.356931e-02
Viscosity [Pa-s]             2.355055e-05  2.288181e-05  2.887508e-05
Prandtl                      3.023834e+00  2.633648e+00  6.988593e+00
```

[18]:
```
# Plot States on T-S Diagram
S_CO2_1 = []
S_CO2_2 = []
T_CO2 = []
T = 273.125 # K

for x in range(0,20000):
    CO2_S = RP.REFPROPdll("CO2","TQMASS","S", MASS_BASE_SI,0,0, T + 31*(x/
↪20000), 0,[1.0]).Output[0]
    S_CO2_1.append(CO2_S/1000)
    CO2_S = RP.REFPROPdll("CO2","TQMASS","S", MASS_BASE_SI,0,0, T + 31*(x/
↪20000), 1,[1.0]).Output[0]
    S_CO2_2.append(CO2_S/1000)
    T_CO2.append(T + 31*(x/20000))
```

[19]:
```
T_CO2_P1 = []
T_CO2_P2 = []
S_P1 = []
T_CO2_P3 = []

for x in range(0,1000):
    CO2_T = RP.REFPROPdll("CO2","PS","T", MASS_BASE_SI,0,0, 1.723700e+07, (1 + .
↪8 * (x/1000))*1000 ,[1.0]).Output[0]
    T_CO2_P1.append(CO2_T-273.125)
    S_P1.append(1 + .8 * (x/1000))
    CO2_T = RP.REFPROPdll("CO2","PS","T", MASS_BASE_SI,0,0, 8.351911e+06, (1 + .
↪8 * (x/1000))*1000 ,[1.0]).Output[0]
    T_CO2_P2.append(CO2_T-273.125)
```

[20]:
```
Isentropic_T = [sCO2_States.loc['Temperature [K]', 'State 1␣
↪Isentropic'],sCO2_States.loc['Temperature [K]', 'State 2'],sCO2_States.
↪loc['Temperature [K]', 'State 3 Isentropic'],\
                sCO2_States.loc['Temperature [K]', 'State 4'],sCO2_States.
↪loc['Temperature [K]', 'State 1 Isentropic'] ]
Actual_T = [sCO2_States.loc['Temperature [K]', 'State 1'],sCO2_States.
↪loc['Temperature [K]', 'State 2'],sCO2_States.loc['Temperature [K]', 'State␣
↪3'],\
                sCO2_States.loc['Temperature [K]', 'State 4'],sCO2_States.
↪loc['Temperature [K]', 'State 1'] ]
S_Isentropic = [sCO2_States.loc['Entropy [J/kg]', 'State 1␣
↪Isentropic'],sCO2_States.loc['Entropy [J/kg]', 'State 2'],sCO2_States.
↪loc['Entropy [J/kg]', 'State 3 Isentropic'],\
                sCO2_States.loc['Entropy [J/kg]', 'State 4'],sCO2_States.
↪loc['Entropy [J/kg]', 'State 1 Isentropic'] ]
```

```
S_Actual = [sCO2_States.loc['Entropy [J/kg]', 'State 1'],sCO2_States.
↪loc['Entropy [J/kg]', 'State 2'],sCO2_States.loc['Entropy [J/kg]', 'State␣
↪3'],\
                sCO2_States.loc['Entropy [J/kg]', 'State 4'],sCO2_States.
↪loc['Entropy [J/kg]', 'State 1'] ]
```

[21]:
```
T_merge = [31,31]
S_merge = [1.415, 1.45]
Isentropic_T = np.array(Isentropic_T) - 273.125
Actual_T = np.array(Actual_T) - 273.125
S_Isentropic = np.array(S_Isentropic)/1000
S_Actual = np.array(S_Actual)/1000
T_CO2 = np.array(T_CO2) - 273.125
```

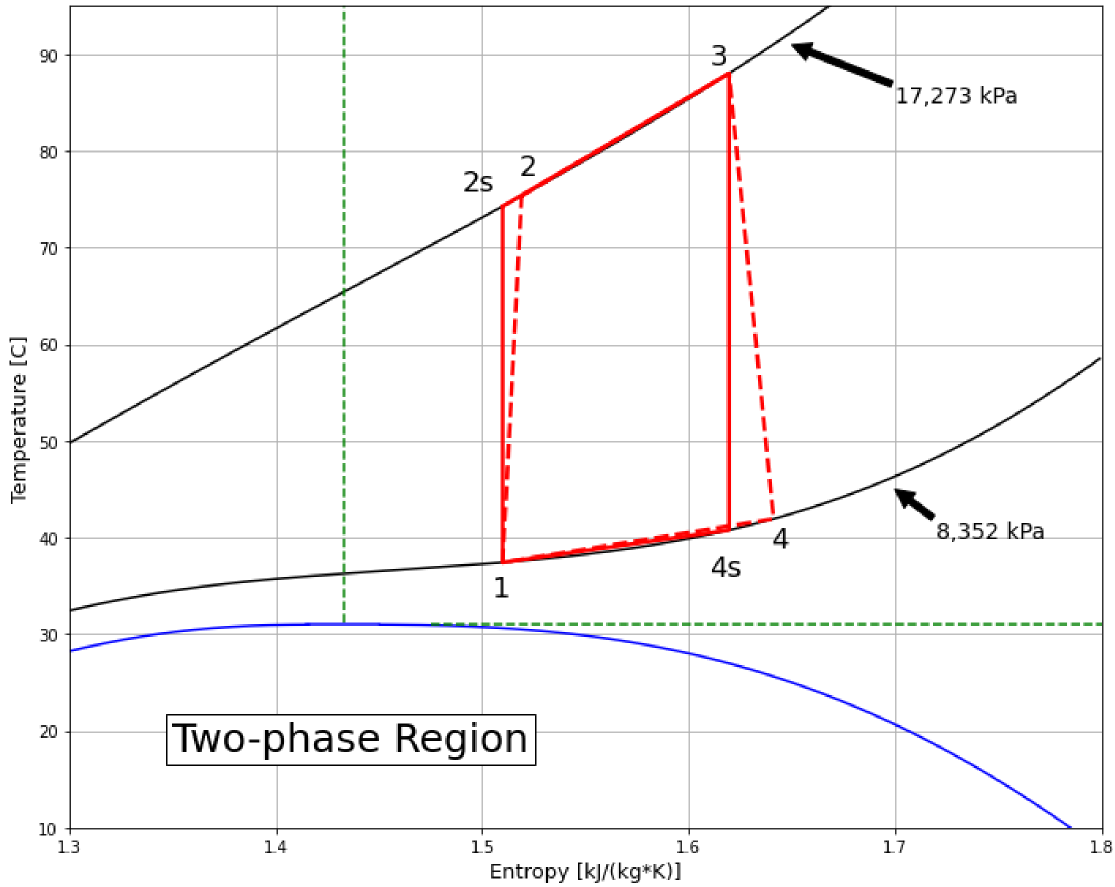
[24]:
```
plt.figure(figsize=(10,8), tight_layout=True)

plt.plot(S_CO2_1, T_CO2, 'b', linewidth = 1.5 )
plt.plot(S_CO2_2, T_CO2, 'b', linewidth = 1.5 )
plt.plot(S_merge, T_merge,'b', linewidth = 1.5)
plt.plot(S_P1, T_CO2_P1,'k',linewidth=1.5)
plt.plot(S_P1, T_CO2_P2,'k',linewidth=1.5)
plt.axvline(x = 1.4331, ymin= .25,  color = 'g', linestyle = '--')
plt.axhline(y=31, xmin = .35, color = 'g', linestyle = '--')
plt.plot(S_Isentropic, Isentropic_T, '-r', linewidth = 2.5)
plt.plot(S_Actual, Actual_T, '--r', linewidth = 2.5)

plt.grid(True)
plt.xlabel('Entropy [kJ/(kg*K)]', fontsize = 13)
plt.ylabel('Temperature [C]', fontsize = 13)
plt.axis([1.3,1.8,10,95])
plt.annotate('8,352 kPa', xy = (1.7, 45), fontsize = 14, xytext = (1.72,␣
↪40),arrowprops = dict(facecolor = 'black'),
             color = 'k')
plt.annotate('17,273 kPa', xy = (1.65, 91), fontsize = 14, xytext = (1.7,␣
↪85),arrowprops = dict(facecolor = 'black'),
             color = 'k')
plt.text(1.505, 34, '1', fontsize = 18)
plt.text(1.518, 77.5, '2', fontsize = 18)
plt.text(1.49, 76, '2s', fontsize = 18)
plt.text(1.61, 89, '3', fontsize = 18)
plt.text(1.61, 36, '4s', fontsize = 18)
plt.text(1.64, 39, '4', fontsize = 18)
plt.text(1.35, 18, 'Two-phase Region', fontsize = 25,
        bbox = dict(facecolor = 'white'))

plt.savefig('T-S_Diagram.png',bbox_inches='tight')
```

```
plt.show()
```



3
17,273 kPa
2s
2
4
8,352 kPa
1
4s
Two-phase Region
Temperature [C]
Entropy [kJ/(kg*K)]

[ ]: